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1.Introduction

The inner part of a fusion reactor will have to operate at very high neutron loads. In steady-state reactors the minimum fluence before the scheduled replacement of the reactor core should be at least 10-15 Mw·yr/m^2. A more frequent replacement of the core is hardly compatible with economic constraints. A most recent summary of the discussions of these issues is presented in Ref. [1]. If and when times come to build a commercial fusion reactor, the availability of information on the behavior of materials and components at such fluences will become mandatory for making a final decision.

This makes it necessary an early development and construction of a neutron source for fusion material and component testing. In this paper, we present information on one very attractive concept of such a source: a source based on a so called Gas Dynamic Trap. This neutron source was proposed in the mid 1980s (Ref. [2]; see also a survey [3] with discussion of the early stage of the project). Since then, gradual accumulation of the relevant experimental information on a modest-scale experimental facility GDT at Novosibirsk, together with a continuing design activity, have made initial theoretical considerations much more credible. We believe that such a source can be built within 4 or 5 years.

Of course, one should remember that there is a chance for developing steady-state reactors with a liquid (and therefore continuously renewable) first wall [4], which would also serve as a tritium breeder. In this case, the need in the neutron testing will become less pressing. However, it is not clear yet that the concept of the flowing wall will be compatible with all types of steady-state reactors. It seems therefore prudent to be prepared to the need of a quick construction of a neutron source.

It should also be mentioned that there exist projects of the accelerator-based neutron sources (e.g., [5]). However, they generally have two major disadvantages: a wrong neutron spectrum, with a considerable excess of high-energy neutrons, and smaller test volume. In addition their development requires considerable investments into non-fusion-related technologies, whereas the work on plasma-type sources would certainly boost technology of fusion energy. Broad discussion of these issues can be found in Refs. [3, 6,7].

2. Some general constraints

We assume that the neutron source will not have a tritium-breeding blanket. The reason for that is that the source should be a user facility and should therefore be based only on proven and reliable technologies, to which the tritium breeding technology does not belong (one can note parenthetically that the source itself could be used for development of the tritium breeding blankets). In addition, it should be remembered that the space around the plasma will be packed with material samples and reactor components undergoing testing; these components would absorb the neutron flux and make therefore the tritium breeding even more difficult.

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So, the source will have to be a tritium-consuming facility. There is a direct relationship between the source strength S (which we will measure in megawatts of a neutron power produced in D-T reactions) and the tritium consumption μ:

$$\mu(g/yr) = 70S(MW) \qquad (1)$$

So, if the source operates with a 100% availability for 1 year at a neutron power of 1 MW, it consumes 70 g of tritium. With the world production of tritium declining, the tritium consumption becomes a serious limitation, which strongly favors sources with moderate source strengths. One example: If a certain source produces neutron flux of, say, 1.5 MW/m^2, it would take 10 full operation years to accumulate a fluence of 15 MW/m^2. If the source strength is, say, 25 MW, the source would have to consume a prohibitive amount of 17.5 kg of tritium. In this sense, the GDT-based neutron source, which would consume no more than 200-250 g of tritium per full operation year, and can provide fluences in the range of 2 MW/m^2 has a serious advantage over many other designs of the plasma neutron sources.

For a given S, it is easy to find electric power P required to sustain the plasma. It is

$$P=1.25S/\eta Q, \qquad (2)$$

where Q is the usual plasma gain, η is the efficiency of a heating system, and the numerical factor 1.25 takes into account the fact that neutrons carry 80% of the fusion energy. Combining Eqs. (1) and (2), one finds the lower limit for the operational cost of the facility:

$$C(\$M/yr) > S(MW)\left(7\cdot 10^{-2} C_T(\$/g) + \frac{11C_E(\$/kWh)}{\eta Q}\right) \qquad (3)$$

where C_T (in \$ per g) and C_E (in \$ per kWh) are costs of tritium and electricity. For the projected cost of tritium ~$3\cdot 10^4$ \$/g and C_E~0.04 \$/kWh, the operational cost becomes

$$C(\$M/yr) > S(MW)\left(2.1 + \frac{0.44}{\eta Q}\right) \qquad (4)$$

For the systems with a modest fusion gains and correspondingly small values of $\eta Q<0.2$, the contributions from tritium and energy consumption are comparable. One also sees that running the sources with a total strength S exceeding a few megawatts is quite costly - giving advantage to compact sources of the type of the GDT source.

3. Physics considerations

The gasdynamic trap [8] is an axisymmetric mirror machine with a very high mirror ratio R~30-50, and a mirror-to-mirror length L exceeding an effective mean free path λ_I/R for the ion scattering into the loss-cone,

$$L > \lambda_i lnR/R \qquad (5)$$

For a target plasma used in the neutron source (T<1 keV, n~ 10^{14} cm^{-3}) $\lambda_i lnR/R$ is ~10 m.

The inequality (5) guarantees that the loss-cone is filled with the plasma particles and the distribution function is near-Maxwellian. This, in turn, means that plasma losses through the mirrors are governed by standard gas-dynamic equations (whence, the name of the device) and the plasma axial confinement is not affected by plasma microinstabilities (which are of a very serious concern for the other types of mirror devices).

Another very important advantage of the GDT is its axial symmetry. As was shown in [8], the magnetohydrodynnamic (MHD) stability in this system (unlike in the conventional mirrors) can be provided by a stabilizing contribution of the plasma beyond the mirror points, where the magnetic field lines are convex toward the plasma. The MHD stability of the gas dynamic trap has been studied experimentally [9], and a good agreement with the theory has been found. The axial symmetry of the magnetic system makes it very simple and flexible, and allows one to produce quite high magnetic field in the mirror throats (20-25 T).

The MHD beta limit in the axisymmetric geometry is typically quite high, in the range of 30-50% [10]. In recent experiments on the GDT device at Novosibirsk [11], Fig. 1, beta values of 30% have been achieved without any signs of the confinement degradation.

The electron heat losses to the end walls set the value of the electron temperature. If the secondary emission from the end walls is negligible, the electron temperature follows classical estimates for the mirror devices [12] and turns to be sufficiently high not only for an efficient neutron source but even for a fusion reactor (specific estimates of the electron temperature for the gas-dynamic trap setting have been made in [2]). An important new circumstance predicted theoretically [13] and confirmed experimentally [14] is that, by making expansion ratio of the magnetic field $E=B_{mirror}/B_{wall}$ in the end tanks high enough, one can sustain high secondary emission without any degradation of the electron confinement. The factors contributing to this favorable outcome include a flattening of electrostatic potential profile at $E>(M/m)^{1/2}$ [13], and a strong mirroring effect experienced by the secondary electrons on their way from the wall to the mirror throat. The combination of these two factors allows one to eliminate the penetration of the secondary electrons into the mirrors by a proper choice of the length of the expansion region (making its length greater than the scattering length for the secondary electrons), or by arranging for a non-normal intersection of the magnetic field with the end wall (then the secondary electrons acquire a considerable cross-field velocity in the Debye sheath and are reflected from the mirror). Therefore, one can state that a once much-feared problem of electron heat losses along the open field lines has found a simple and reliable solution.

In order to generate a high neutron flux, it was suggested in [2] to inject high energy tritons (~ 100 keV or more) at a small angle to the magnetic field. As the scattering of fast ions takes longer time than their drag on relatively cold electrons, this approach would result in a strong concentration of the fast ions near their turning point in a strong magnetic field, giving rise to a localized zone of a high neutron flux. In [15], a version with a shallow-angle injection of both deuterons and tritons into the target plasma has been analyzed. This version would allow one to reduce the injection energy to ~80 keV and, thereby, use a more mature technology of neutral beams based on the acceleration of positive ions. Both schemes rely on the assumption that the sloshing ions behave classically. The validity of this assumption has been demonstrated experimentally at the GDT device, where detailed measurements of the distribution function of fast ions have been carried out [16].

4. Neutron source

Schematic of a neutron source based on these physics principles is shown in Fig. 2. The most important parameters of the source are listed in Table 1. The parameters presented in Table 1 correspond just to one possible version of the neutron source. By changing the injection power, injection angle, and the plasma radius, one can vary the total source strength, the neutron flux, and the dimensions of the test zone in a broad range.

This neutron source has several important advantages: 1) Low tritium consumption, below 200 G per one year of a continuous operation; 2) High neutron flux in a volume exceeding 100 l; 3) Low neutron (<0.1 MW/m^2) and heat (<0.6 MW/m^2) load at the most part of the device except the test zone; 4) Low neutron load in the zone of neutral beam injectors; 5) Small tritium inventory (related both to the small size of the source and small tritium consumption); 6) Inherently steady-state operation (with a possibility, if so desired, of modulating neutron flux at the frequency up to a few kHz); 7) Simplicity (and, therefore, low cost) of the magnetic system.

The source does not require any significant extrapolations from presently existing technologies. Perhaps, the only element whose development requires considerable efforts, is a CW neutral beam injector, but such injectors are needed for many other fusion devices and will have to be developed anyway. The cost estimates of the neutron source range from $ 250 M to $ 500 M, depending on the specific version of the source and location of the source site.

TABLE 1 Parameters of the GDT-based neutron source

NB energy. keV	70
Neutral beam power, MW	30
Injection angle, ^{0}	30
Mirror-to-mirror length, m	10
Plasma radius in the midplane, m	0.08
Magnetic field strength in the midplane, T	1.3
Magnetic field strength in the mirrors, T	20
Electron density in the midplane, cm^{-3}	$2 \cdot 10^{14}$
Electron temperature, keV	0.75
Source strength, MW	2
The length of the test zone, m	1,5
Inner diameter of the test zone, m	0.1
Neutron flux in the test zone, MW/m^2	2

It is important to note that the source can be developed in steps. For example, one could first build the magnetic and vacuum system, plus NBI, and operate the source with hydrogen and small amount of deuterium, thereby making the device essentially non-radioactive. After having made the necessary tests, one could add expensive elements related to the presence of tritium, and bring the source to the full operation.

Some design activity of the GDT source goes on at a modest level. Participants are several Russian institutions, two German nuclear research centers (Karlsruhe and Rossendorf), and Italian center in Frascati. Recently, a summary talk on this concept has been presented by Dr. hennies, a co-director of the Karlsruhe center [17].

5. Discussion

The participation in the mirror-based neutron source development and renewing at some level mirror research in general could be a useful addition to the U.S. fusion program. The reasons for this conclusions are as follows:

1) Construction of a facility similar to the GDT device at Novosibirsk guarantees obtaining a plasma with respectable parameters at a low cost. The potentialities of such a device for the studies of a broad range of plasma physics issues related to plasma behavior on the open field lines cannot be overestimated. From the experience of building the GDT device in the mid 1980s and its later upgrading, the cost of building a similar facility in the U.S. can be estimated as $ 3 M.

2) With modest additional investments at the level of $ 10 M, it is possible to build a considerably improved version of the gas-dynamic trap, with higher magnetic field in the midplane (1 T instead of 0.22 T), higher NBI power (15 MW instead of 4 MW), with a longer pulse (100 or more ms instead of 1 ms). The most important improvement in plasma parameters in such a device should be an increased electron temperature (300 eV instead of 120 eV), and a higher density of the 10-20 keV sloshing ions near the turning points (~

10^{14} cm^{-3} instead of $2 \cdot 10^{13}$ cm^{-3}). Plasma physics involved will be of a considerable interest not only for fusion research but also for the solar physics and the physics of magnetosphere. The device, being axisymmetric, will be very flexible and will allow, in particular, considerable changes of the magnetic configuration.

3) Involvement in these activities would allow the U.S. fusion community to fully realize its previous experience in the studies of mirror systems and mirror-based neutron sources (e.g., [18]).

4) Construction of the source, either on the international (or a national - the source is not an excessively expensive device) basis would be a very important step to show the usefulness of fusion energy. The source would become the first man-made (steady-state) fusion device that would be a user facility (and not yet another large-scale experiment). It would serve not only fusion science but also medical science, biology, solid-state physics, nuclear physics, astrophysics, etc. The success of this device would probably change the attitude of a broader science community and politicians to fusion program in general.

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In addition to being an excellent candidate for evolving into a high-flux neutron source, the gasdynamic trap has interesting potentialities as a fusion reactor. This is extremely simple and reliable system. Its only drawback as a fusion reactor, is a large unit power, in the range of 4-5 GW, and a large length (~ 1-2 km). These parameters do not look too attractive in the present energy marketplace. However, the situation may change considerably in the coming decades. Therefore, it would be prudent to keep an eye on this system also as an energy-producing facility.

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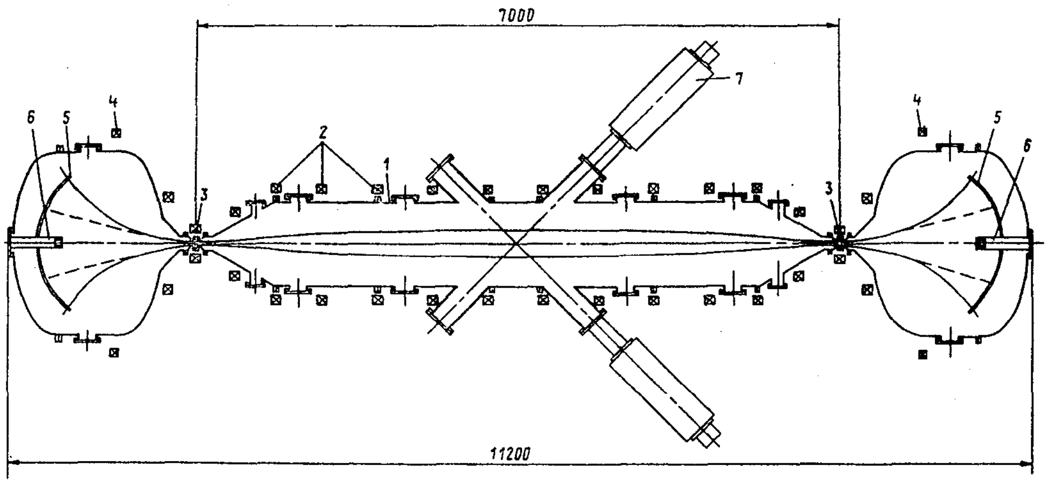

Fig. 1 Schematic of the GDT device. Dimensions are given in mm. 1) Central vacuum chamber; 2) Coils of a central solenoid; 3) Mirror coils; 4) Coils controlling magnetic field in the end tanks and allowing to change it from stabilizing (solid lines) to neutral (dashed lines); 5) Plasma absorber; 7) Neutral beam injectors.

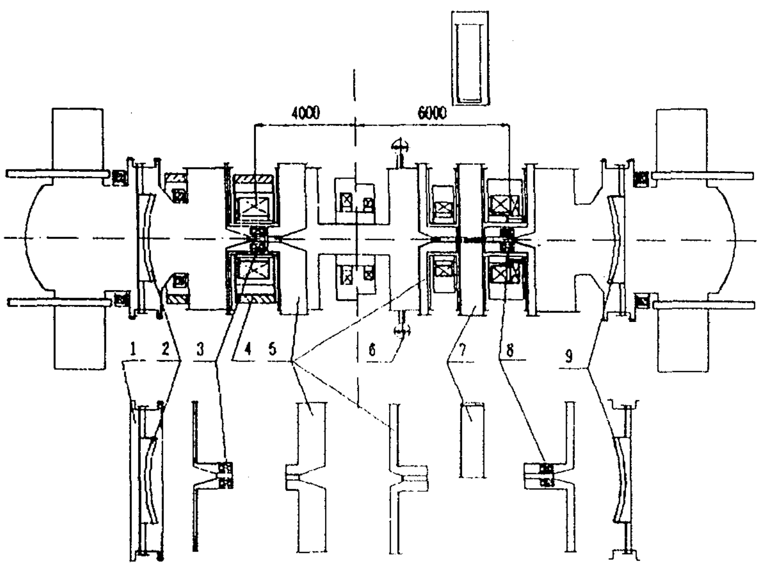

Fig. 2 Schematic of a neutron source; dimensions are given in mm. 1) End section; 2) Plasma absorber; 3) Resistive solenoid; 4) Magnetic screen; 5) Test zone for continuous irradiation; 6) Pellet injector; 7) Test zone for short-term irradiation; 8) Resistive coil; 9) Plasma absorber.